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Unified TeV Scale Picture of Baryogenesis and Dark Matter

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Abstract

We present a simple extension of MSSM which provides a unified picture of cosmological baryon asymmetry and dark matter. Our model introduces a gauge singlet field N and a color triplet field X which couple to the right-handed quark fields. The out-of-equilibrium decay of the Majorana fermion N mediated by the exchange of the scalar field X generates adequate baryon asymmetry for $M_N \sim 100$ GeV and $M_X \sim \text{TeV}$. The scalar partner of N (denoted \tilde{N}_1) is naturally the lightest SUSY particle as it has no gauge interactions and plays the role of dark matter. \tilde{N}_1 annihilates into quarks efficiently in the early universe via the exchange of the fermionic \tilde{X} field. The model is experimentally testable in (i) neutron-antineutron oscillations with a transition time estimated to be around 10^{10} sec, (ii) discovery of colored particles X at LHC with mass of order TeV, and (iii) direct dark matter detection with a predicted cross section in the observable range.

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I. INTRODUCTION

The origin of matter–anti-matter asymmetry of the Universe and that of dark matter are two of the major cosmological puzzles that rely heavily on particle physics beyond the standard model for their resolution. It is a common practice to address these two puzzles separately by invoking unrelated new physics. For instance, a widely held belief is that either the lightest supersymmetric particle (LSP) or the near massless invisible axion constitutes the dark matter, while baryogenesis occurs through an unrelated mechanism involving either the decay of a heavy right-handed neutrino (leptogenesis), or new weak scale physics which makes use of the electroweak sphalerons. A closer examination of the minimal versions of SUSY would suggest that to generate the required amount of dark matter density, one needs some tuning of parameters. The LSP should either have the right amount of Higgsino component, or another particle, usually the right-handed stau, should be nearly degenerate (to within a few GeV) with the Bino LSP to facilitate dark matter co-annihilation. Similarly, the leptogenesis mechanisms requires the heavy right-handed neutrino to have its mass in the right range to generate the adequate amount of matter. Despite these possible problems, these ideas are attractive since they arise in connection with physics scenarios which are strongly motivated by other puzzles of the standard model, e.g., resolving the gauge hierarchy problem (in the case of LSP dark matter) or generating small neutrino masses (in the case of leptogenesis). However until such time as there is experimental confirmation of these ideas, it is quite appropriate to entertain other explanations of these phenomena which could be motivated on other grounds. Our motivation here is to seek a unified picture of both these cosmological puzzles within the context of weak scale supersymmetry without any fine-tuning of parameters. We propose a class of models where a very minimal extension of the MSSM seems to resolve both these puzzles in a natural manner with testable consequences for the near future.

Our extension of MSSM involves the addition of two new particles: a SM singlet superparticle denoted by N with mass in the 100 GeV range and an iso-singlet color triplet particle X with mass in the TeV range. These particle, consistent with the usual R -parity assignment, couple only to the right-handed quarks. We discuss two models: one in which the electric charge of X is $2/3$ and another where it is $-1/3$. We show that in these models, baryon asymmetry arises by the mechanism of post-sphaleron baryogenesis suggested by us

in a recent paper [1] involving the decay of the fermionic component of N . The scalar component of N (denoted as \tilde{N}_1) has all the right properties to be the cold dark matter of the universe without any fine-tuning of parameters. The purpose of the heavier X particle is to facilitate baryon number violation in the interaction of N , and also to help \tilde{N}_1 annihilate into quarks. A very interesting prediction of these models is the existence of the phenomenon of neutron-anti-neutron oscillation with a transition time in the accessible range of around 10^{10} sec. which could be used to test the models. The TeV scale X particle which is an essential ingredient in making the \tilde{N}_1 a viable dark matter is detectable at LHC. Furthermore, the model predicts observable direct detection cross section for the dark matter.

II. OUTLINE OF THE MODEL

As already noted, we add two new superfields to the MSSM – a standard model singlet N and a pair of color triplet with weak hypercharge $= \pm 4/3$ denoted as X, \bar{X} . The R -parity of the fermionic component of N is even, while for the fermionic X it is odd. This allows the following new terms in the MSSM superpotential (model A):

$$W_{new} = \lambda_i N u_i^c X + \lambda'_{ij} d_i^c d_j^c \bar{X} + \frac{M_N}{2} N N + M_X X \bar{X}. \quad (1)$$

Here i, j are family indices with $\lambda'_{ij} = -\lambda'_{ji}$ and we have suppressed the color indices. An alternative possibility is to choose X to have hypercharge $-2/3$ and write a superpotential of the form (model B)

$$W_{new} = \lambda_j N d_j^c X + \lambda'_{kl} u_k^c d_l^c \bar{X} + \frac{M_N}{2} N N + M_X X \bar{X}. \quad (2)$$

In model B, other couplings involving X are allowed which could for example lead to rapid proton decay. One can guarantee that such terms are suppressed by additional discrete symmetries. In model A however, there are no other terms that are gauge invariant and R -parity conserving. We will illustrate our mechanism using model A although all our discussions will be valid for model B as well.

The fermions N and \tilde{X} have masses M_N and M_X respectively. As for the scalar components of these superfields, the Lagrangian including soft SUSY breaking terms is given by

$$-\mathcal{L}_{\text{scalar}} = |M_X|^2(|X|^2 + |\bar{X}|^2) + m_X^2|X|^2 + m_{\bar{X}}^2|\bar{X}|^2 + \quad (3)$$

$$(B_X M_X X \overline{X} + h.c.) + |M_N|^2 |\tilde{N}|^2 + m_{\tilde{N}}^2 |\tilde{N}|^2 \\ + \left(\frac{1}{2} B_N M_N \tilde{N} \tilde{N} + h.c.\right)$$

The 2×2 mass matrix in the (X, \overline{X}^*) sector can be diagonalized to yield the two complex mass eigenstates X_1 and X_2 via the transformation

$$X = \cos \theta X_1 - \sin \theta e^{-i\phi} X_2; \\ \overline{X}^* = \sin \theta e^{i\phi} X_1 + \cos \theta X_2$$
(4)

where

$$\tan 2\theta = \frac{|2B_X M_X|}{|m_X^2 - m_{\overline{X}}^2|}; \quad \phi = \text{Arg}(B_X M_X) \text{sgn}(m_X^2 - m_{\overline{X}}^2). \quad (5)$$

Note that the angle θ is nearly 45° if the soft masses for X and \overline{X} are equal. The two mass eigenvalues are

$$M_{X_{1,2}}^2 = |M_X|^2 + \frac{m_X^2 + m_{\overline{X}}^2}{2} \pm \left[\left(\frac{m_X^2 - m_{\overline{X}}^2}{2} \right)^2 + |B_X M_X|^2 \right]^{1/2}. \quad (6)$$

The two *real* mass eigenstates from the \tilde{N} field have masses

$$M_{\tilde{N}_{1,2}}^2 = m_{\tilde{N}}^2 + |M_N|^2 \pm |B_N M_N|. \quad (7)$$

Here \tilde{N}_1 is the real part of \tilde{N} , while \tilde{N}_2 is the imaginary part. (A field rotation on \tilde{N} has been made so that the $B_N M_N$ term is real.) With these preliminaries we can now discuss baryogenesis and dark matter in our model.

III. POST-SPHALERON BARYOGENESIS

The mechanism for generation of matter-anti-matter asymmetry closely follows the post-sphaleron baryogenesis scheme of Ref. [1]. As the universe cools to a temperature T which is below the mass of the X particle but above M_N , the X particles annihilate leaving the Universe with only SM particles and the N (fermion) and $\tilde{N}_{1,2}$ (boson) particles in thermal equilibrium. The decay of N will be responsible for baryogenesis. We therefore need to know the temperature at which the interactions of N go out of equilibrium. We first consider its decay. Being a Majorana fermion, N can decay into quarks as well as antiquarks: $N \rightarrow u_i d_j d_k$, $N \rightarrow \bar{u}_i \bar{d}_j \bar{d}_k$. The decay rate for the former is

$$\Gamma(N \rightarrow u_i d_j d_k) = \frac{C}{128} \frac{(\lambda^\dagger \lambda) \text{Tr}[\lambda'^\dagger \lambda']}{192\pi^3} \sin^2 2\theta M_N^5 \left(\frac{1}{M_{X_1}^2} - \frac{1}{M_{X_2}^2} \right)^2. \quad (8)$$

Here the approximation $M_{X_{1,2}} \gg M_N$ has been made. C is a color factor, equal to 6. The total decay rate of N is twice that given in Eq. (8) - to account for decays into quarks as well as into antiquarks. As a reference, we take the contribution from X_1 exchange to dominate the decay, and assume that the mixing angle $\theta \simeq 45^\circ$. It is then easy to see that for $\sqrt{(\lambda^\dagger \lambda) \text{Tr}[\lambda'^\dagger \lambda']}$ $\sim 10^{-4}$, N decay goes out of equilibrium below its mass. Other processes involving N such as $q + N \rightarrow \bar{q} + \bar{q}$ also go out of equilibrium at this temperature. Further, for $T < M_N$, production of N in $q + q$ scattering will be kinematically inhibited.

The decay of N , which is CP violating when one-loop corrections are taken into account, can lead to the baryon asymmetry. Since the mass of the N fermion is below the electroweak scale, the sphalerons are already out of equilibrium and cannot erase this asymmetry. The mechanism is therefore similar to the post-sphaleron baryogenesis mechanism a la Ref. [1]. The only difference from the detailed model in Ref. [1] is that, there, due to the very high dimension of the decay operator, the out of equilibrium temperature was above the decaying particle (called S in Ref. [1]) mass giving an extra suppression factor of T_d/M_S in the induced asymmetry (since generation of matter has to start when the temperature is much below the S particle mass). In the present case, there is no suppression factor of T_d/M_S in the induced baryon asymmetry.

In order to calculate the the baryon asymmetry of the universe, we look for the imaginary part from the interference between the tree-level decay diagram and the one-loop correction arising from W^\pm exchange. These corrections have a GIM-type suppression, since the W^\pm only couple to the left-handed quark fields while the tree-level decay of N is to right-handed quarks. Following Ref. [1], we find the dominant contribution to be

$$\frac{\epsilon_B}{\text{Br}} \simeq \left\{ -\frac{\alpha_2}{4} \right\} \frac{\text{ImTr}(\lambda'^T M_u V \lambda'^\dagger V^* M_d)}{M_W^2 \text{Tr}(\lambda'^\dagger \lambda')} \quad (9)$$

where Br stands for the branching ratio into quarks plus anitquarks, and M_u is the diagonal up-quark mass matrix. The interesting point is that as in Ref. [1] the asymmetry is completely determined by the electroweak corrections. If \tilde{N} is lighter than the top quark, then we get

$$\frac{\epsilon_B}{\text{Br}} \simeq - \left\{ \frac{\alpha_2}{4} \right\} \frac{m_c m_b \lambda'_{23} \lambda'_{21} V_{ub} \sin \delta}{M_W^2 |\lambda'_{22}|^2} \quad (10)$$

yielding $\epsilon_B \simeq 3 \times 10^{-8} \frac{\lambda'_{21} \lambda'_{23}}{|\lambda'_{22}|^2}$. (Here we assumed the couplings λ'_{ij} to be real for illustration.) This can easily lead to desired value for the baryon asymmetry for reasonable choice of the coupling parameters λ' . Note that this allows the λ' coupling to remain free parameters.

IV. SCALAR DARK MATTER

In a supersymmetric model, we expect every particle to have a super-partner. We show below that in our extended MSSM the super-partner of N (denoted by \tilde{N}_1) has all the properties quite naturally for it to play the role of scalar dark matter. In this context let us recall some of the requirements on a dark matter candidate: it must be the lightest stable particle and its annihilation cross section must have the right value so that its relic density gives us the $\Omega_{\text{DM}} \simeq 0.25$. The desired cross section for a generic multi-GeV CDM particle is of about 10^{-36} cm^2 . In our model the presence of the TeV scale particle, in addition to playing an important role in the generation of baryon asymmetry, also plays a role in giving the right annihilation cross section for \tilde{N}_1 to be the dark matter.

Let us first discuss why \tilde{N}_1 is naturally the lightest stable boson in our model. To start with, in order to solve the baryogenesis problem, we choose the N superfield to have its mass below that of the super-partners of the SM particles. In mSUGRA type models, generally, one chooses a common scalar mass for all particles at the SUSY breaking scale (say M_P or M_{GUT}), so that scalar masses at the weak scale are determined by the renormalization group running. There are two kinds of contributions to the running of the soft SUSY breaking masses – gauge contributions which increase masses as we move lower in scale, and Yukawa coupling contributions which tend to lower the masses as we move lower in scale. As far as the scalar \tilde{N}_1 particle goes since it has no gauge couplings, its mass naturally goes somewhat lower as we move from the Planck scale to the weak scale and becomes naturally the lowest stable state. Furthermore since its couplings $\lambda_{1,2}$ are in the range of 0.1-0.001, they are not strong enough to drive $m_{\tilde{N}_1}^2$ negative like the $m_{H_u}^2$.

From Eq. (7), it is clear that of the two states $\tilde{N}_{1,2}$, the lighter one \tilde{N}_1 is the LSP. The \tilde{N}_2 remains close in mass but above the LSP and can help in co-annihilation of the dark matter provided $|BM_N| \ll M_N^2 + m_{\tilde{N}}^2$, if needed.

Dark matter annihilation. In the early universe, the LSP \tilde{N}_1 will annihilate into quark-antiquark via the exchange of \tilde{X} fermion. The annihilation cross section is given by

$$\sigma(\tilde{N}_1 \tilde{N}_1 \rightarrow q \bar{q}) v_{\text{rel}} = \frac{C'(\lambda^\dagger \lambda)^2}{8\pi s} \left(\frac{a}{b} \tanh^{-1}\left(\frac{b}{a}\right) - 1 \right) \quad (11)$$

where

$$a = 2E^2 - M_{\tilde{N}_1}^2 + M_{\tilde{X}}^2; \quad b = 2E|\vec{p}|. \quad (12)$$

Here $C' = 3$ is a color factor, E and \vec{p} are the energy and momentum of one of the \tilde{N}_1 , s is the total CM energy. For $M_X \gg E$, the cross section reduces to

$$\sigma v_{\text{rel}} \simeq \frac{1}{8\pi} (\lambda^\dagger \lambda)^2 \frac{|\vec{p}|^2}{M_X^4} \quad (13)$$

For the coupling $\lambda_3 \sim 1$, $M_{\tilde{N}_1} = 300$ GeV and $M_X = 500$ GeV, the cross section is of the order of a pb as would be required to generate the right amount of relic density.

We can now compare this with the dark matter in MSSM, where a linear combination of the Bino and the neutral Higgsino (the neutralino) is essentially taken to play the role of dark matter. In MSSM, some tuning of parameters is needed, either to have the right amount of Higgsino content in the LSP, or to have the right-handed stau nearly mass degenerate with the LSP to facilitate co-annihilation. In our model, there is no need for co-annihilation but if necessary, the mass of \tilde{N}_2 is naturally close to \tilde{N}_1 if $|BM_N|$ is chosen to be small.

Dark matter detection. Due to the fact that \tilde{N}_1 has interactions with quarks which are sizable, it can be detected in current dark matter search experiments. We present an order of magnitude estimate of the \tilde{N}_1 +nucleon cross section. Even though the annihilation cross section is of order 10^{-36} cm², the detection cross section on a nucleon $\sigma_{\tilde{N}_1+p}$ is much smaller due to slow speed of the dark matter particle which limits the final state phase space for the elastic scattering. Secondly, detection involves only the first generation quarks whereas annihilation involves the second generation as well and thus if the N couplings are hierarchical like the SM Yukawa couplings, it is easy to understand the smallness of detection cross sections compared to σ_{ann} . In our model the scattering of \tilde{N}_1 (with momentum p) off a quark (with momentum k) occurs via the s-channel exchange of the fermionic component of X . The amplitude is given by

$$\mathcal{M}_{\tilde{N}_1+q} = i \frac{\lambda_1^2}{4M_X^2} \overline{u(k')} \gamma^\mu u(k) Q_\mu \quad (14)$$

where, $Q = k + p$. At the nucleon level, the time component of the vector current dominates (spin-independent) over the spatial component (velocity dependent). The nucleon- \tilde{N}_1 cross section is given by

$$\sigma_{\tilde{N}_1+p} \simeq \frac{\lambda_1^4 m_p^2}{64\pi M_X^4} \left(\frac{A+Z}{A} \right)^2 \quad (15)$$

where A are the atomic numbers and charge of the nucleus and λ_1 is the coupling of N to the first generation quarks. The sum $\lambda_1^2 + \lambda_2^2$ is constrained by LSP annihilation requirement

but individually λ_1 is not. If we choose $\lambda_1 \sim 0.1$, then the cross section is around 10^{-45} cm^2 which is in the range being currently explored [6].

V. NEUTRON-ANTI-NEUTRON OSCILLATION

One of the interesting predictions of our model is the existence of neutron-anti-neutron oscillation at an observable rate. The Feynman diagram contributing to this process is given in Ref. [2]. Since N is a Majorana fermion, it decays into udd as well as into $\bar{u}\bar{d}\bar{d}$, which leads to $N - \bar{N}$ oscillations. The strength for this process (taking into account the anti-symmetry of λ' couplings) is given by:

$$G_{\Delta B=2} \simeq \frac{(\lambda_1 \lambda'_{12})^2}{M_N M_X^4} \quad (16)$$

The $\Delta B = 2$ operator in this case has the form $u^c d^c s^c u^c d^c s^c$. The couplings appearing in this process are those involving the first generation, analogous to the couplings relevant to direct detection of dark matter. It is reasonable to expect them to be somewhat smaller in magnitude compared to their second generation counterpart. Secondly, if we choose the strange quark component in the nucleon to be about 1%, then choosing $\lambda_1 \lambda'_{12} \simeq 10^{-5}$, we find that $G_{\Delta B=2} \simeq 10^{-27} \text{ GeV}^{-5}$ which corresponds to the present limit on $\tau_{N-\bar{N}} \sim 10^8$ sec. [3, 4]. There are proposals to improve this limit by two orders of magnitude[5] by using a vertical shaft for neutron propagation in an underground facility e.g. DUSEL. It is interesting that the expectation for the $N - \bar{N}$ transition is in the range accessible to experiments and this can therefore be used to test the model.

VI. OTHER ASPECTS OF THE MODEL

(i) The X particle in our model can be searched for at the LHC. Once produced, X will decay into two jets, e.g., a b jet and a light quark jet. We point out that there is an interesting difference in discovery of SUSY at LHC in our model. Consider up type squarks pair produced at LHC. The squark will decay into a quark plus a neutralino. In our model, the neutralino is unstable, it decays into $u^c d^c d^c \tilde{N}$. So one SUSY signal will be six jets plus missing energy. The scalar up squark can also decay directly into $\tilde{N} d^c d^c$. In this case the signature will be 4 jets plus missing energy.

(ii) It is also worth noting that the quantum numbers of N are such that it is a SM singlet with $B - L = 1$ and therefore same as that of the conventional right-handed neutrino. This model can therefore be used to understand the small neutrino masses via a low scale seesaw mechanism provided there are at least two N 's and the Dirac masses for neutrinos are suppressed. We do not dwell on this aspect of the model in this paper since it is not pertinent to our main results. We however point out that our results are not affected by the multi- N extension required for understanding neutrino masses. The RH neutrino which plays the role in generating baryon asymmetry and dark matter is the lightest of the N fields. This model is however different in many respects from some other suggestions of right handed sneutrino dark matter in literature [8, 9, 10].

(iii) The models presented are compatible with gauge coupling unification, provided that the X particle is accompanied by other vector-like states which would make complete $10 + \overline{10}$ representations of $SU(5)$. These extra particles will have no effect on baryogenesis and dark matter phenomenology.

VII. CONCLUSION

In conclusion, we have presented a unified particle physics description of two major problems of cosmology – the baryon asymmetry of the universe and the dark matter. The desired properties of the dark matter seem to come out in a more natural manner than in the MSSM. A prediction of the model is the existence of neutron-anti-neutron oscillation and two classes of new particles beyond MSSM: a color triplet supersymmetric particle and a color singlet right-handed neutrino like particle coupling to quarks. These new particles could therefore be observable at LHC. The cross section for direct dark matter detection is predicted to be in the observable range.

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